Exploring the Ultra High Energy Cosmic Rays with the Pierre Auger Observatory

Sergio Petrera, GSSI and L'Aquila University

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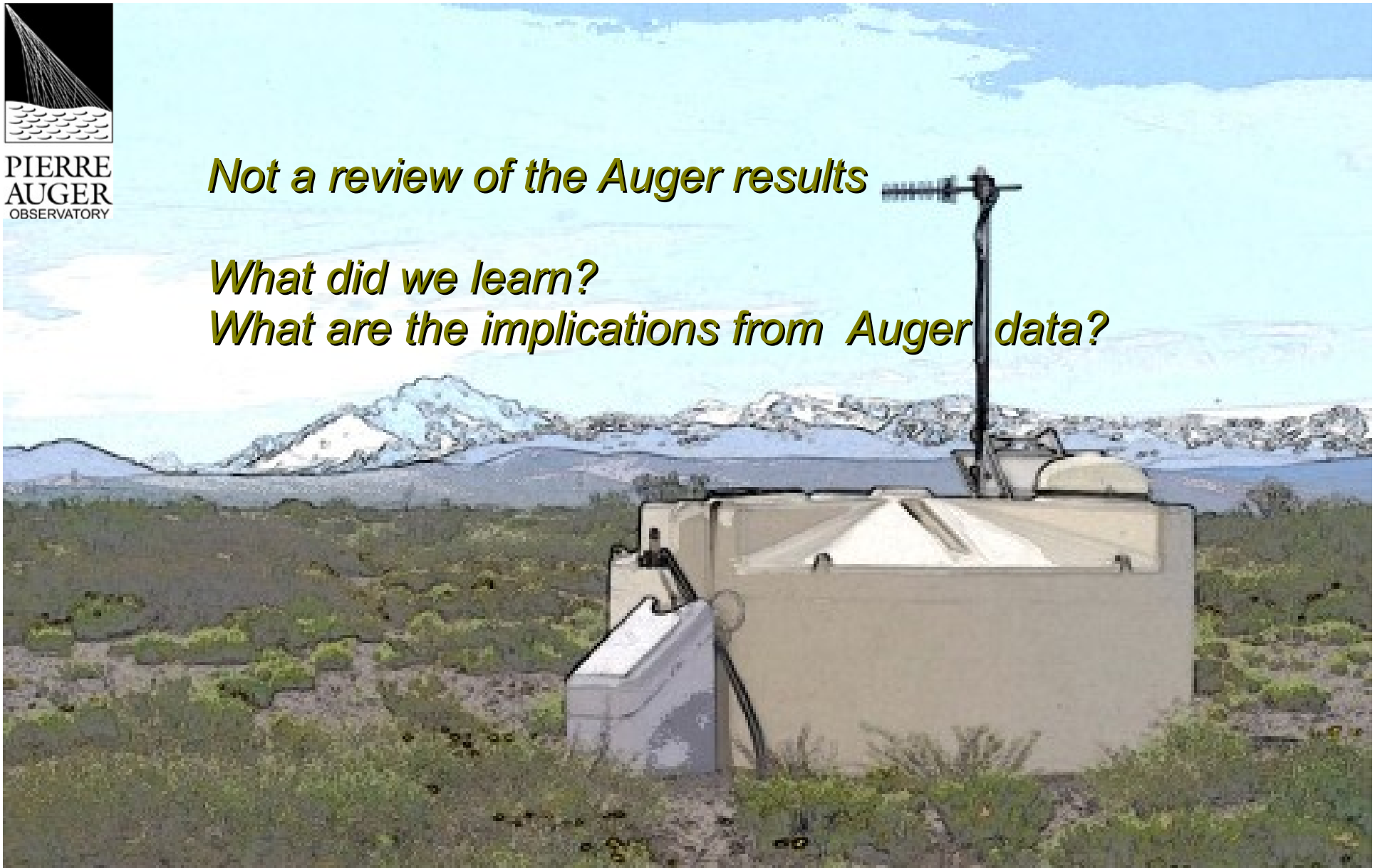
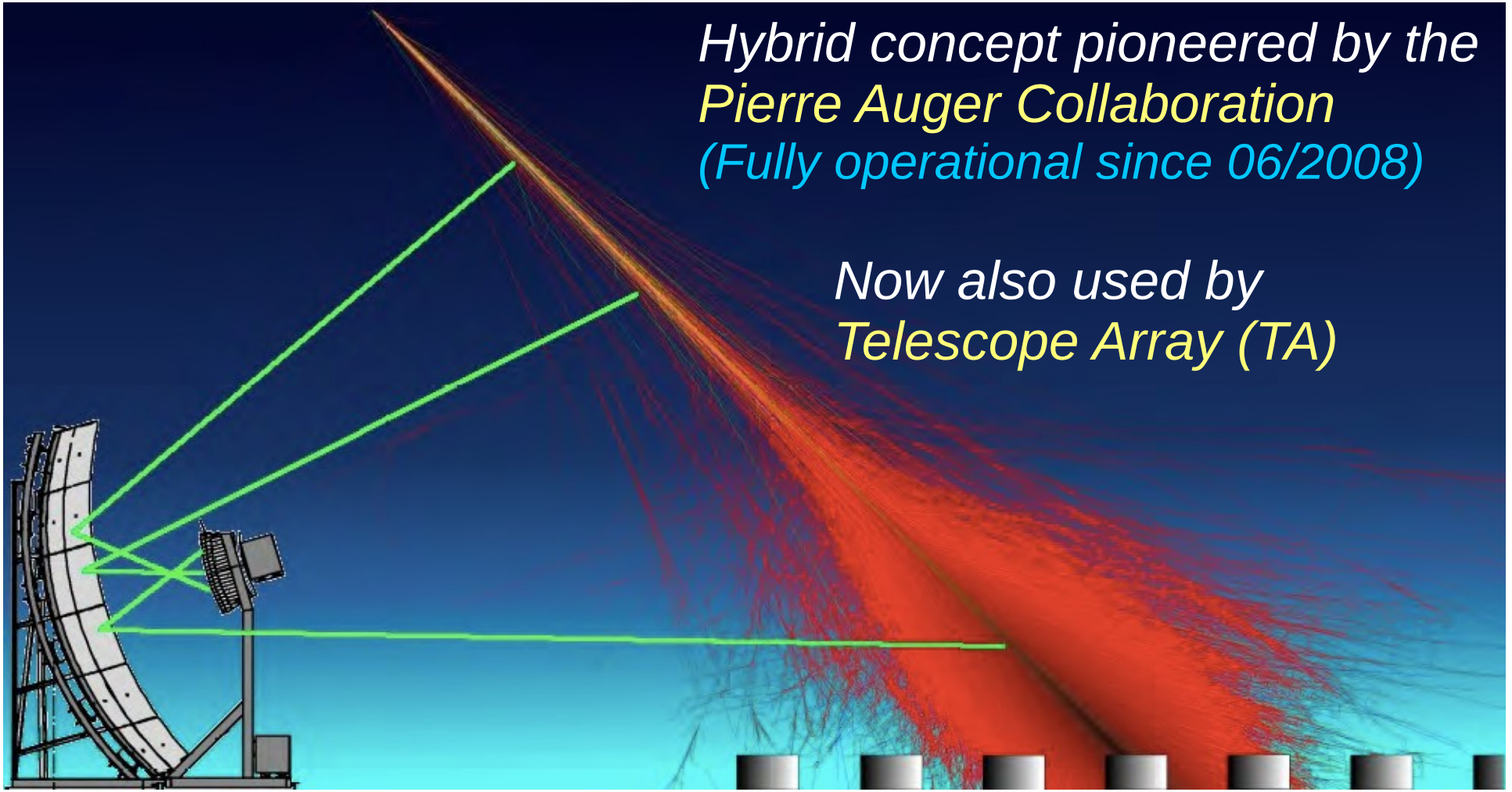


The main inputs to UHECR interpretation

- The Energy Spectrum: two break features
  the ankle: What is the origin?
  the end: GZK-effect or Exhaustion of Sources?
- Mass Composition: getting heavier?!
- Arrival Directions: surprisingly isotropic!
- EeV neutrinos and photons: Foteini's talk
- Further Searches: neutrons, monopoles, particle & shower physics, ...

The experimental method

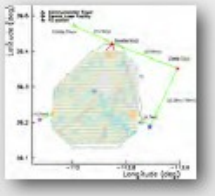


Fluorescence detector:
calorimetric UV light tracing

Surface Detector array:
particle density @ ground

Auger and TA

Telescope Array (TA)
Delta, UT, USA
507 detector stations, 680 km^2
36 fluorescence telescopes

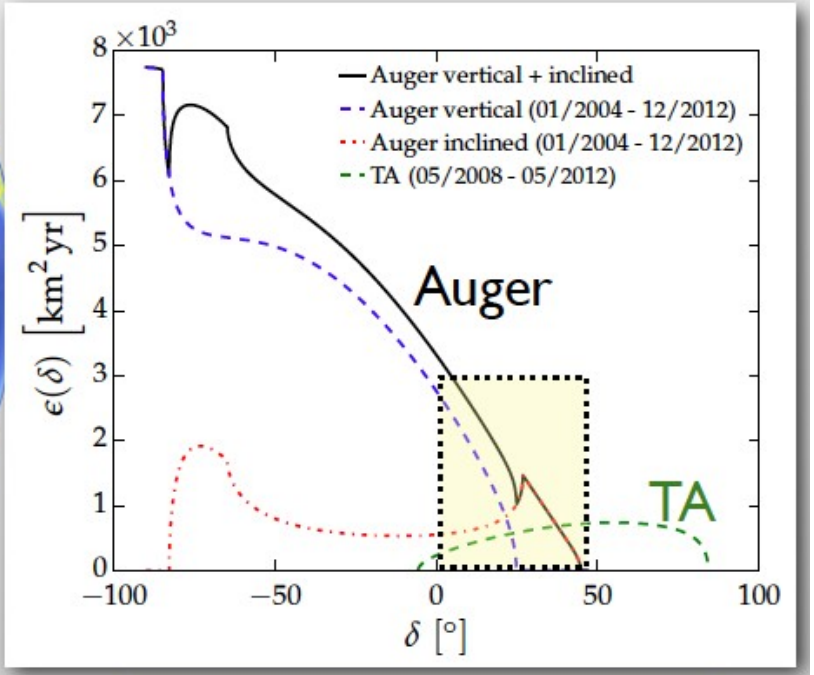


same scale

Pierre Auger Observatory
Province Mendoza, Argentina
1660 detector stations, 3000 km^2
27 fluorescence telescopes

Auger and TA can see the same sky

Auger: 01/2004 - 12/2012
TA: 05/2008 - 05/2012

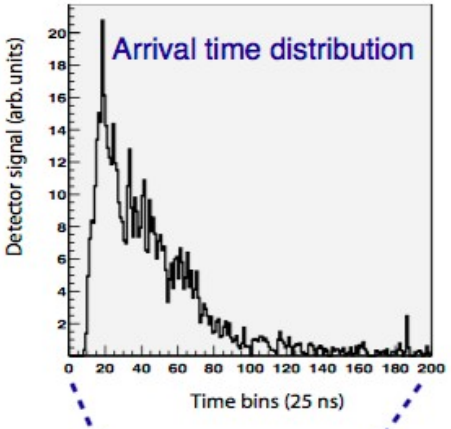


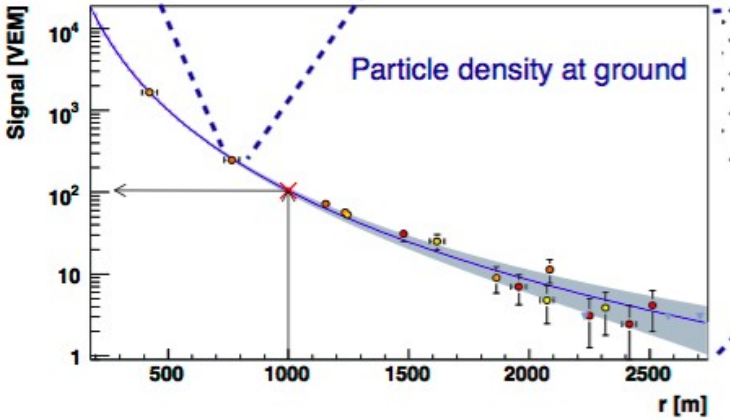
Auger exposure ~8 times that of TA

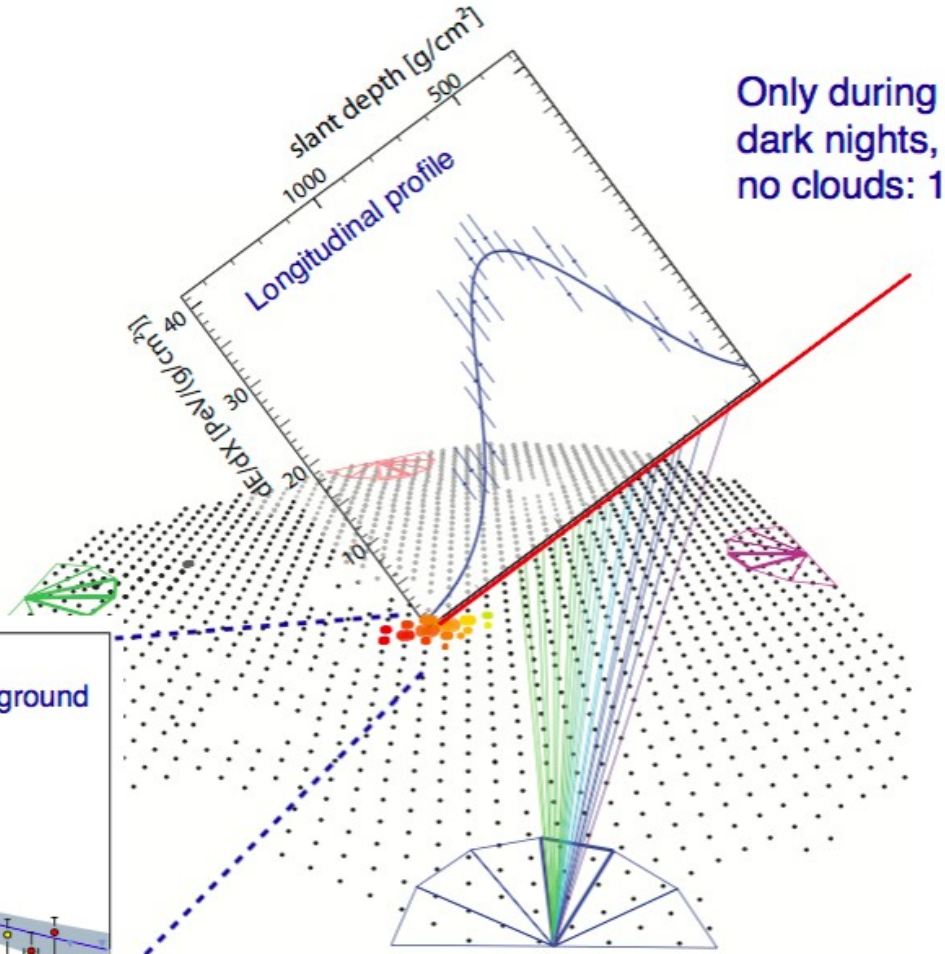
Event reconstruction

- Arrival direction
- Particle energy

Always: 100%



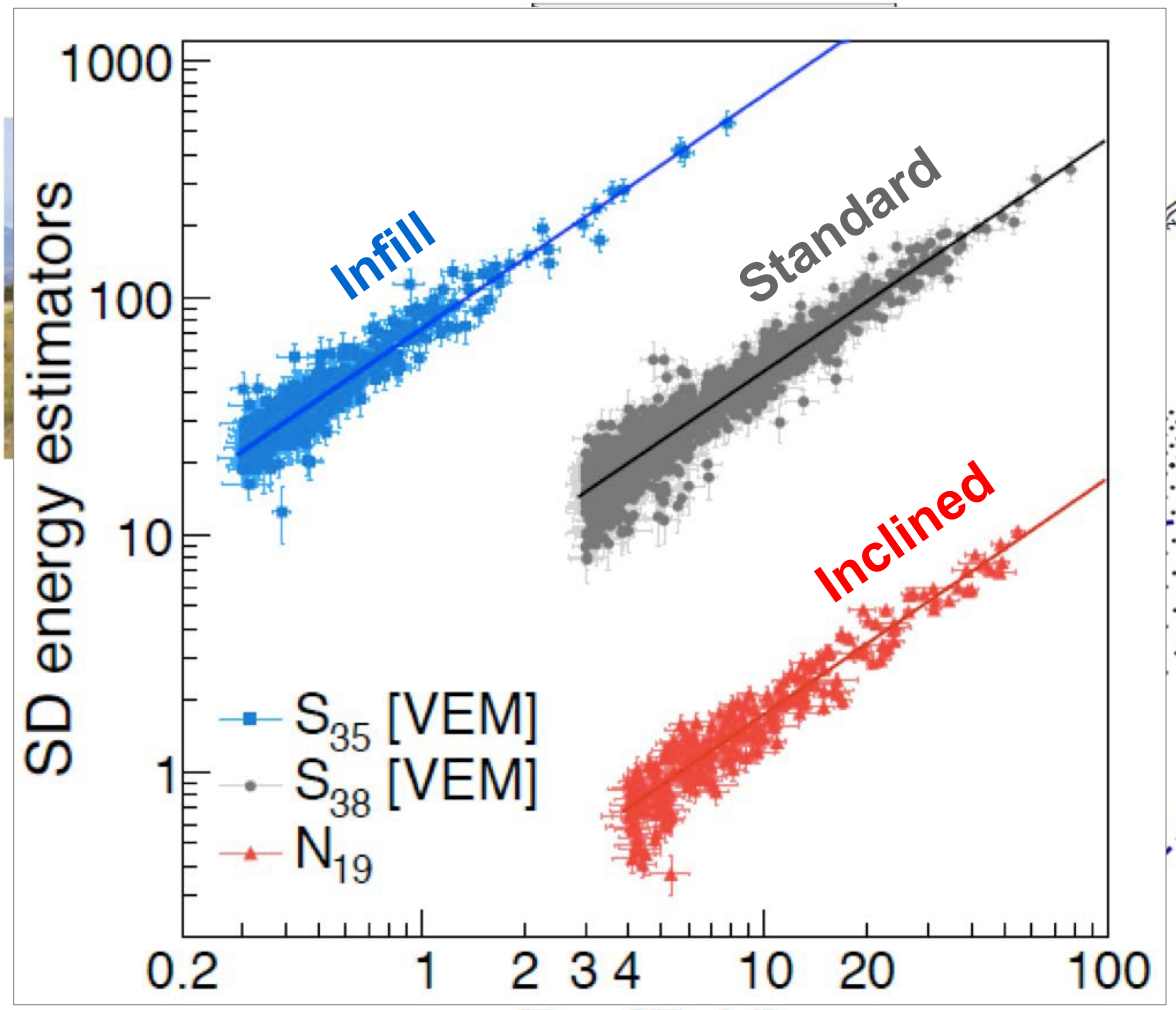


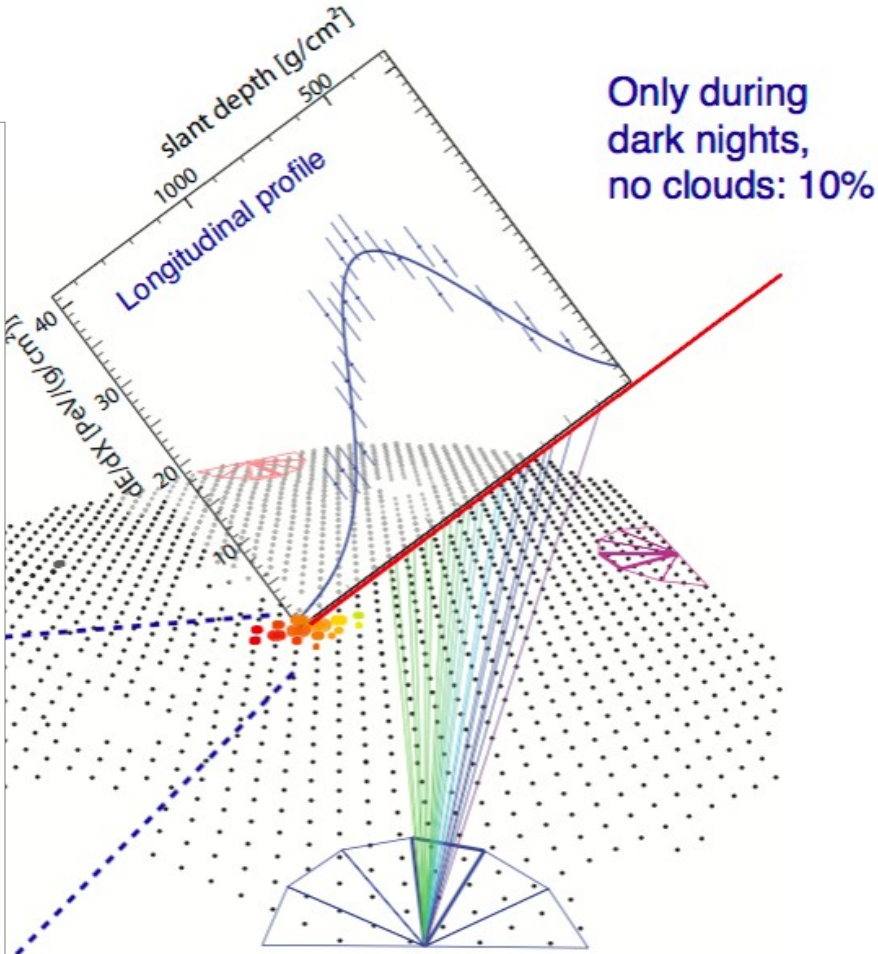


Only during dark nights, no clouds: 10%

Event reconstruction

SD Energy calibration from FD data
(calorimetric) syst ≃ 14%



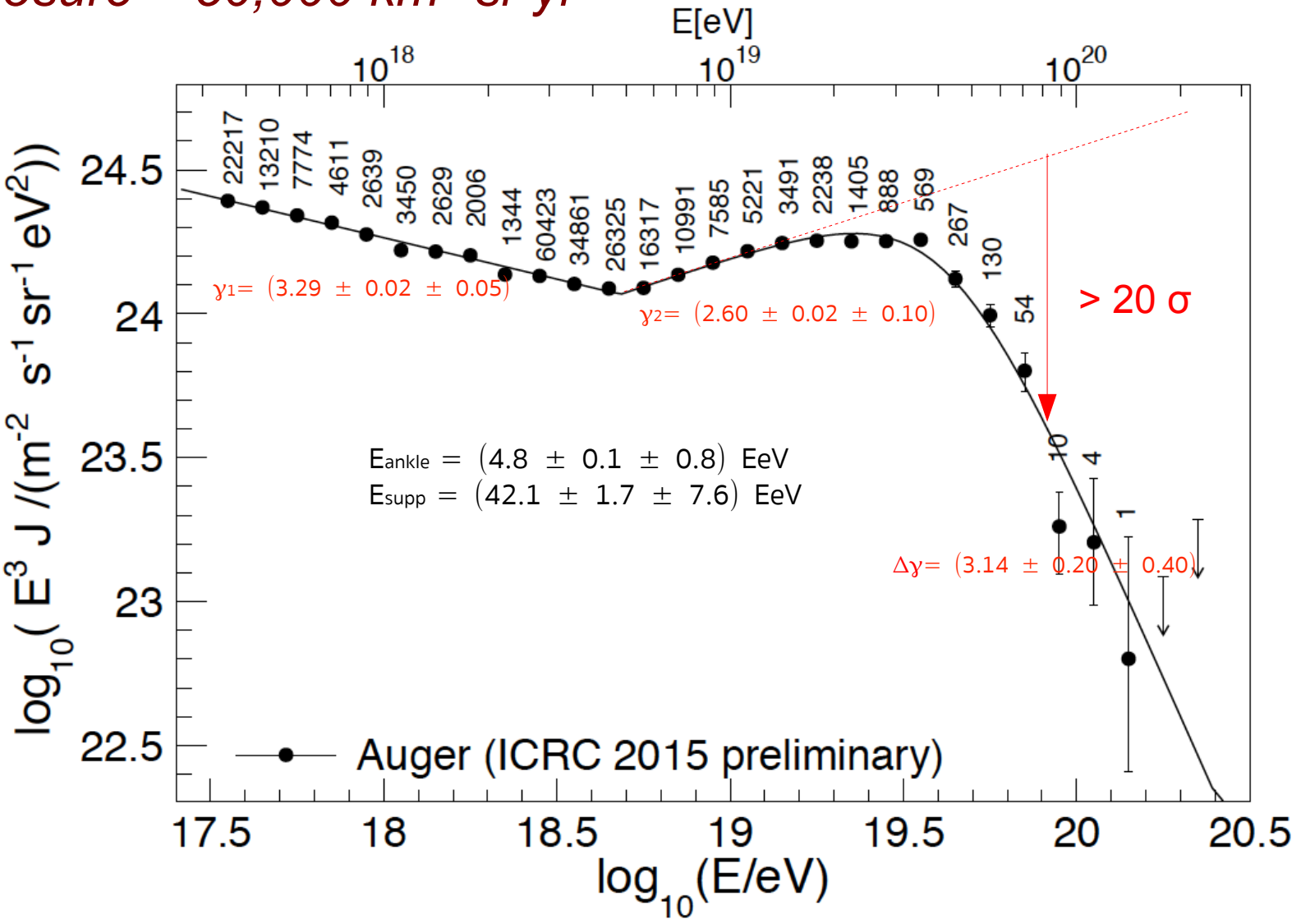


UHECR
Energy Spectrum

Auger Energy Spectrum

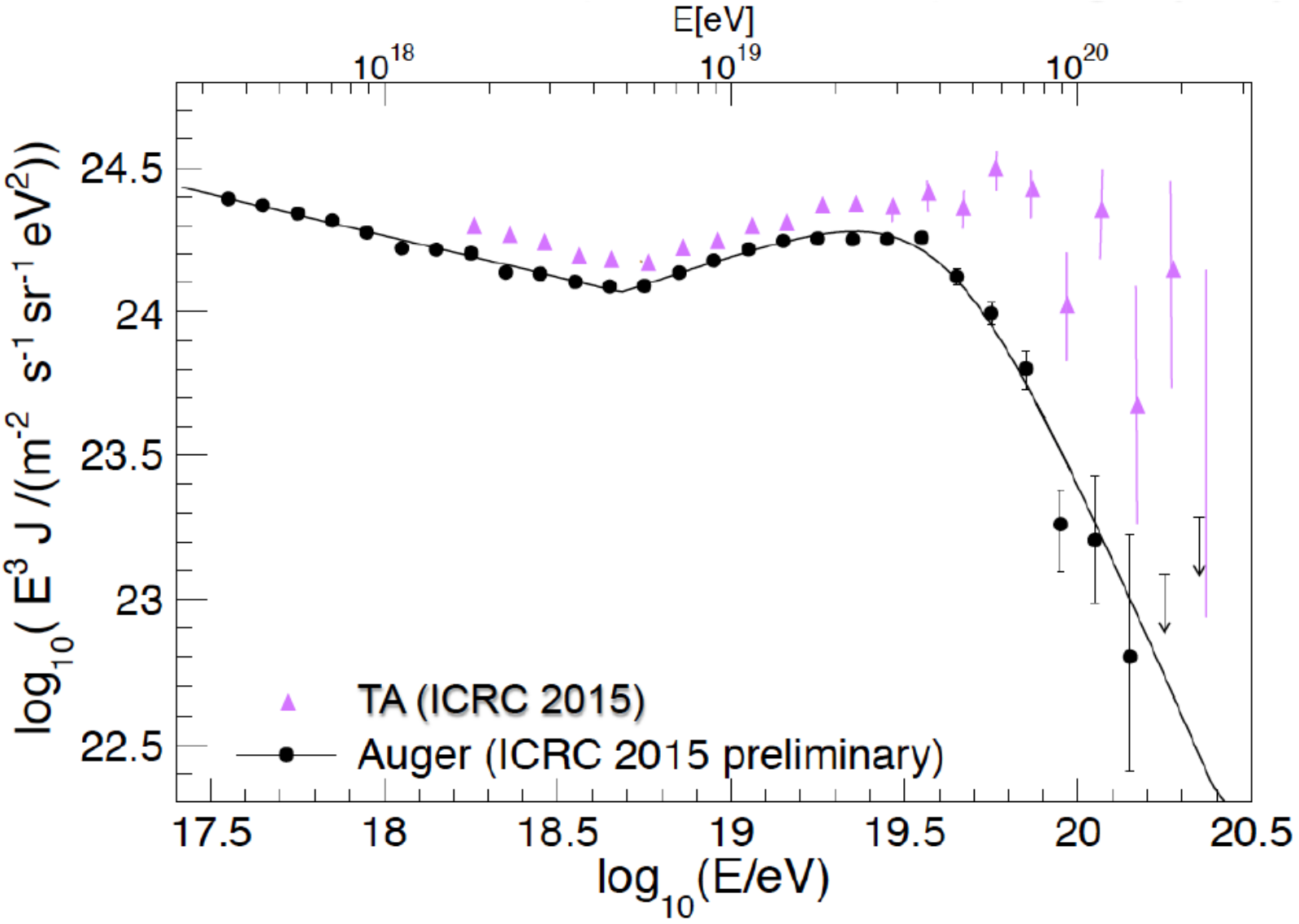
Combined (Infill+Hybrid+SD)

Exposure = 50,000 km^2 sr yr



Auger vs TA

14% *20%* *energy scale uncertainty*



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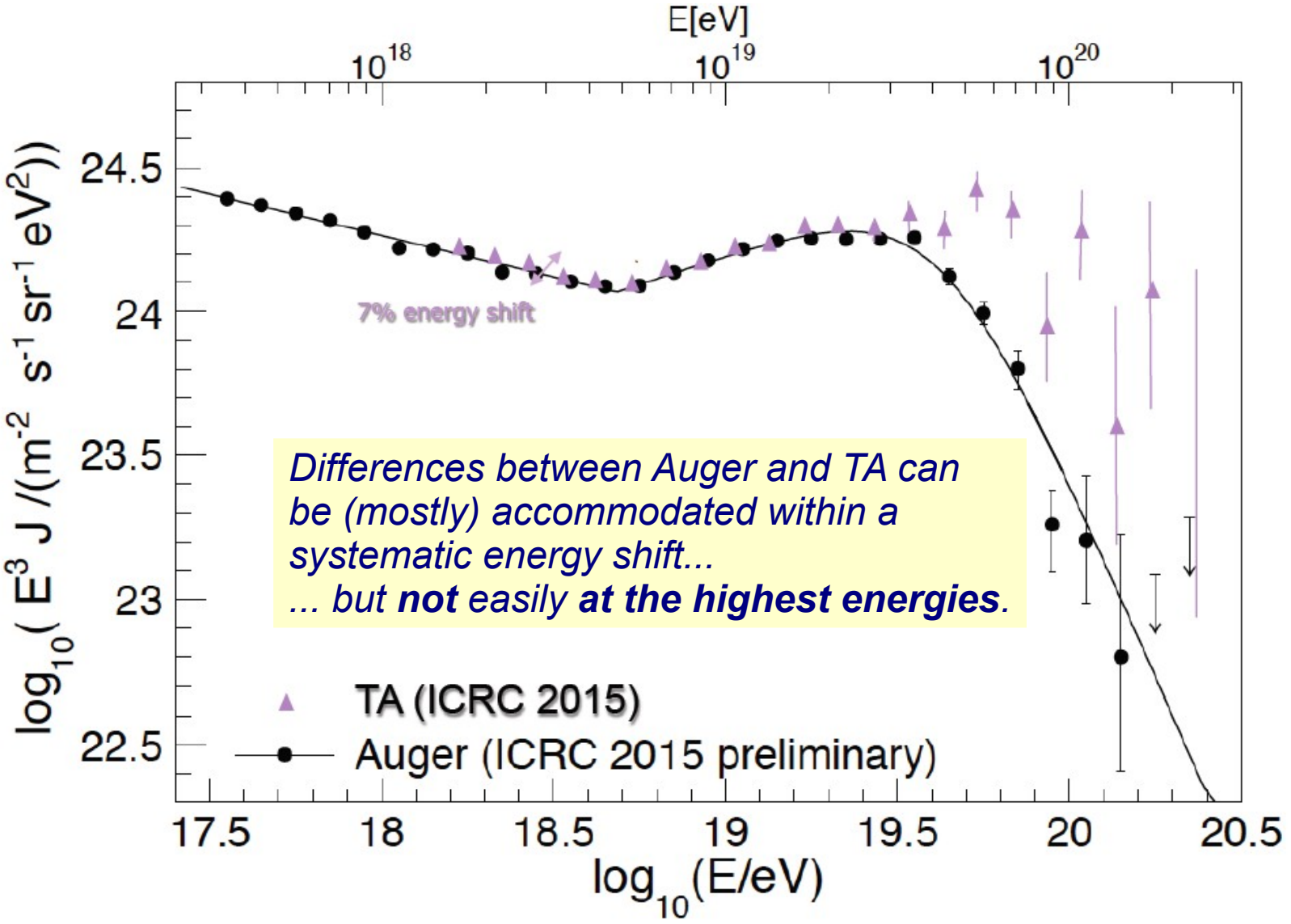
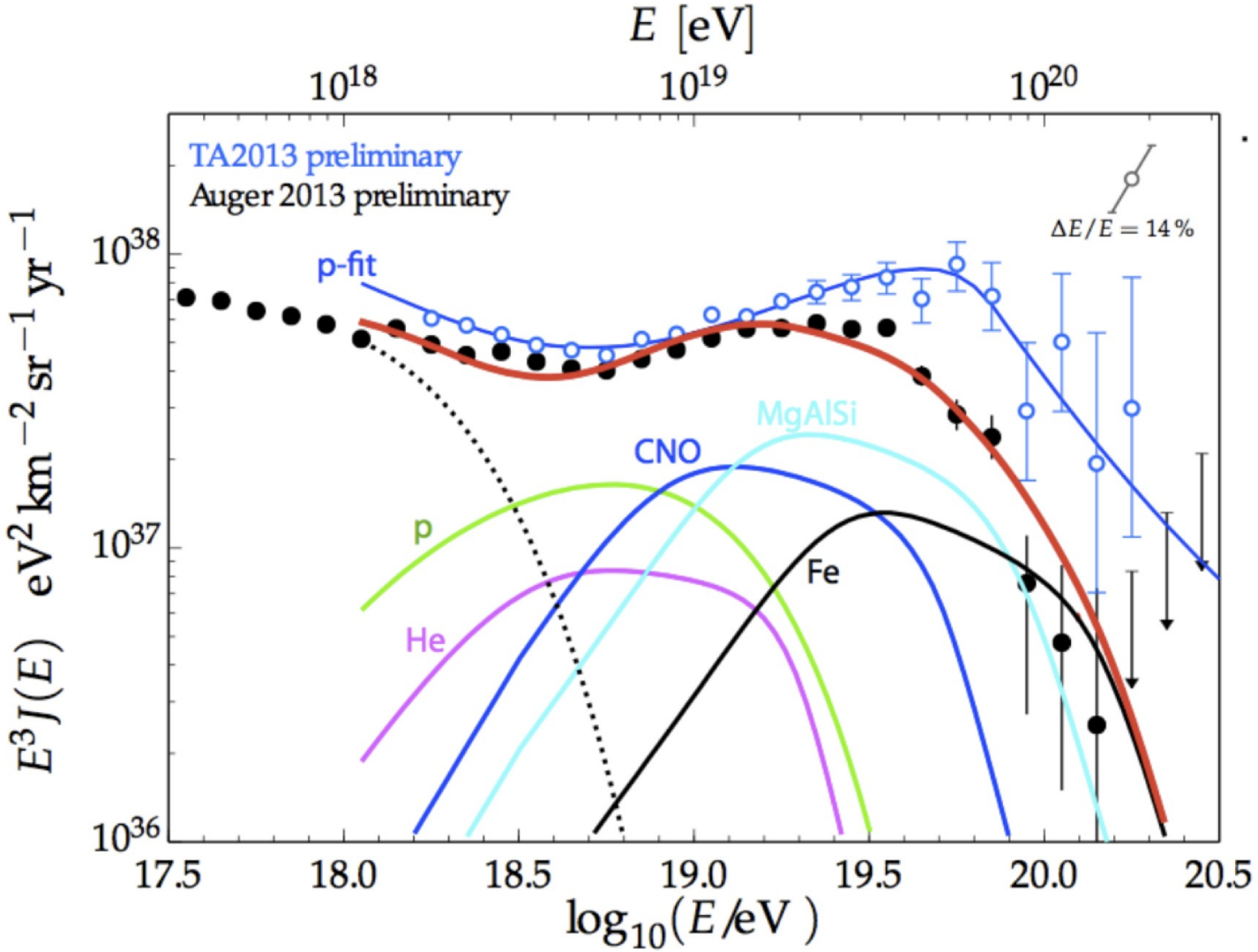


Which Astrophysics Scenario?

V. Berezinsky et al. (2005), R. Aloisio, V. Berezinsky, and A. Gazizov, Astropart. Phys. 39-40 (2012) 129

R. Aloisio, V. Berezinsky, and P. Blasi, JCAP 1410 (2014) 10, 020



K-H. Kampert and P. Tinyakov, arXiv:1405.0575v1

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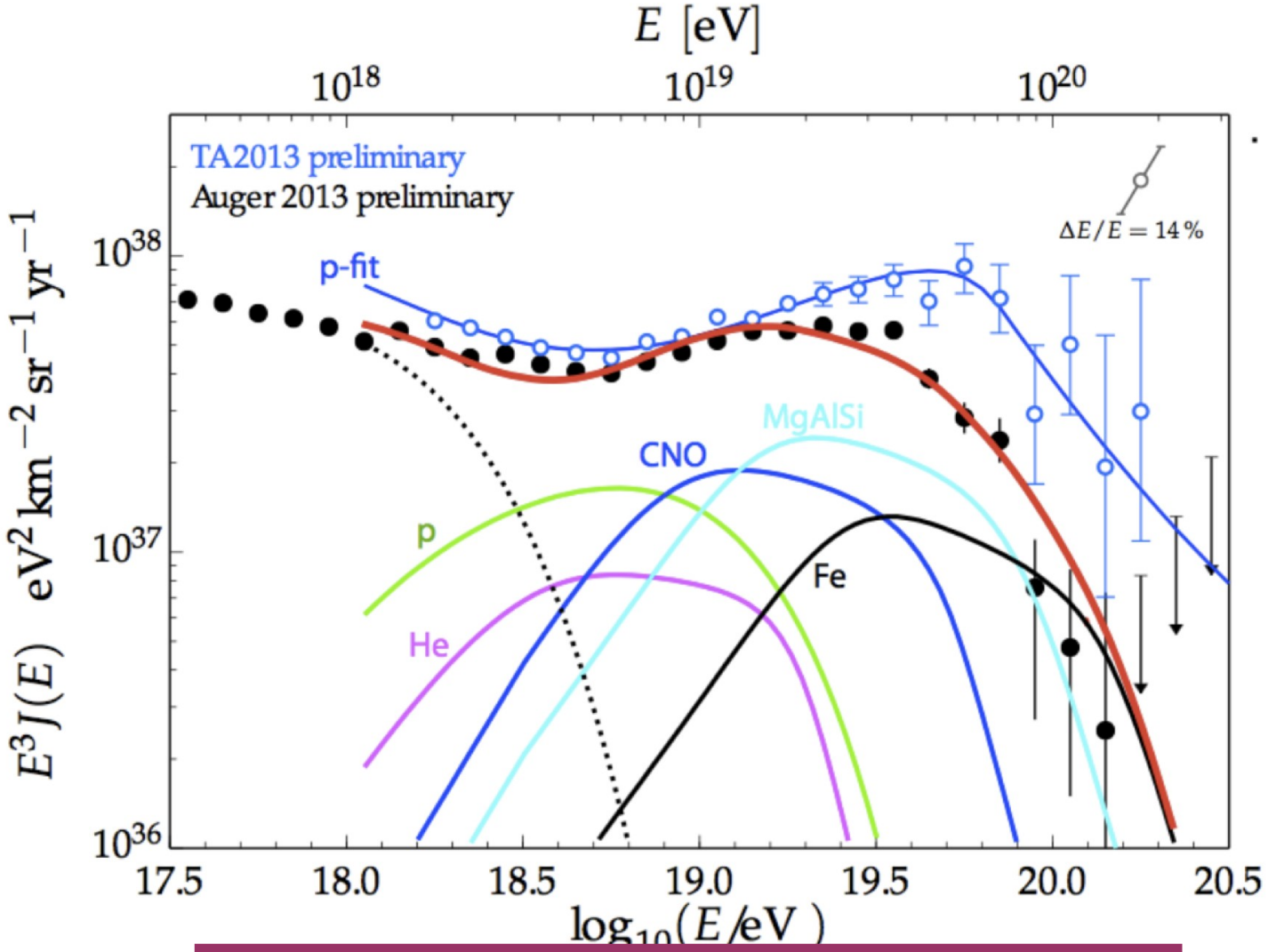


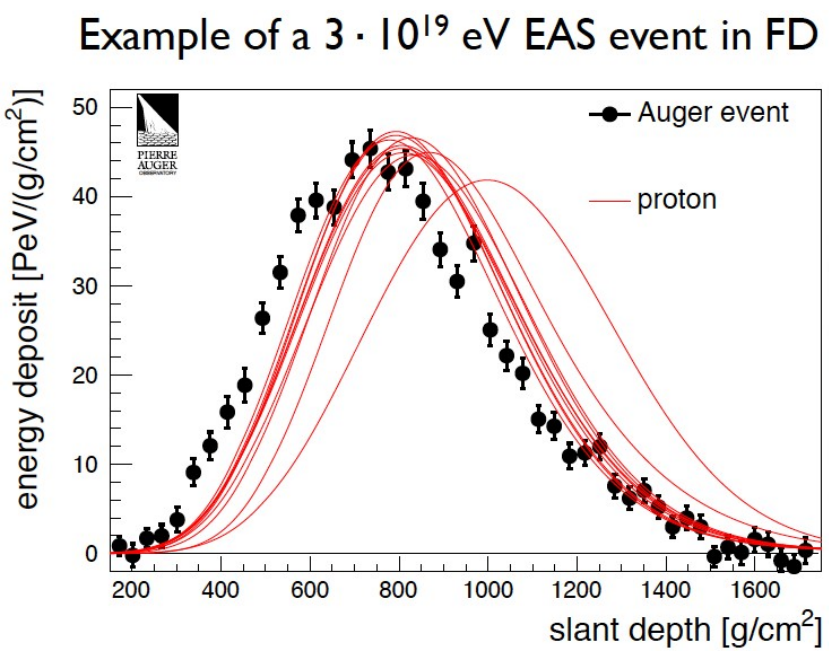
Energy spectrum alone remains ambiguous concerning interpretations → Need mass composition

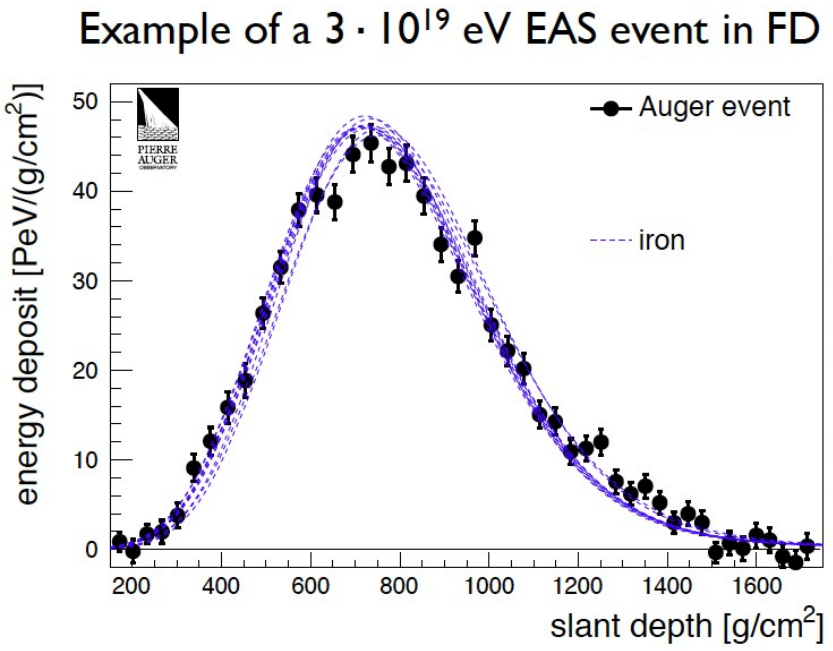
UHECR
Mass Composition

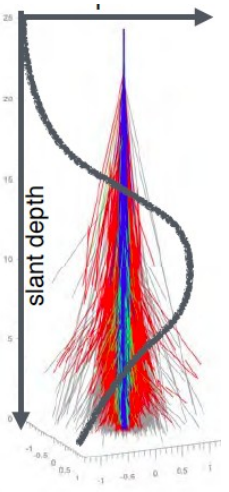
Longitudinal Profiles

Xmax: our best mass estimator, but...

Available only for hybrid events (FD duty cycle ~ 10%)







p-induced showers develop

deeper than

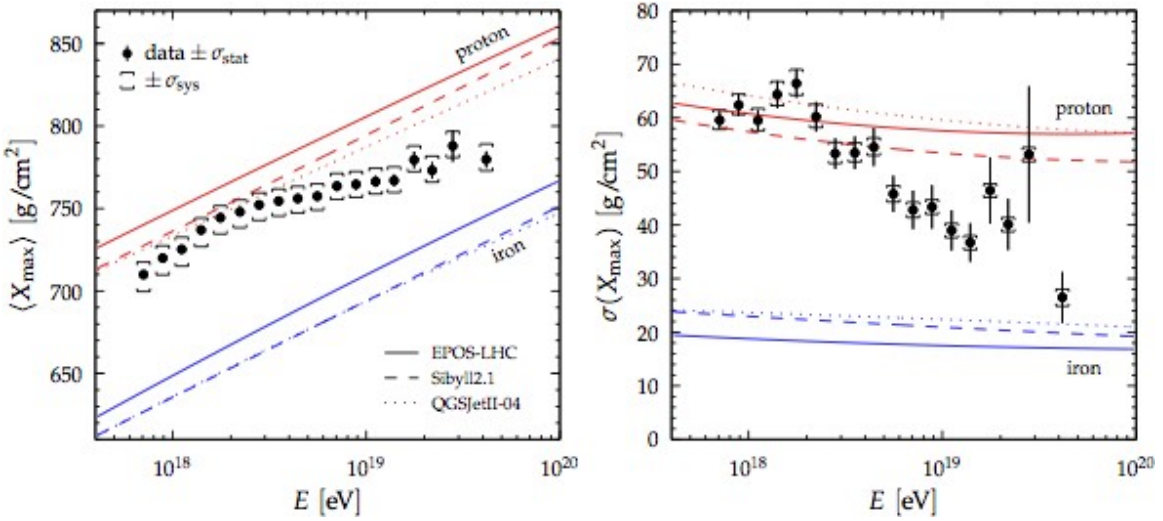
Fe-induced ones

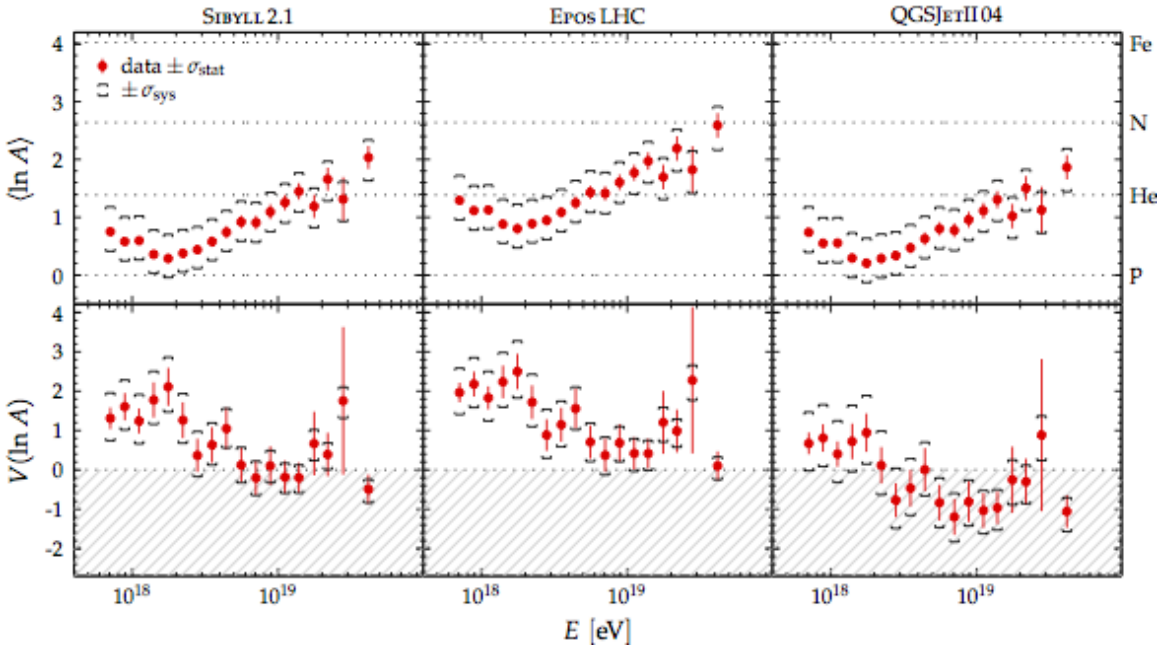
and have larger fluctuations

Longitudinal Profiles

Xmax

Auger data from clean hybrid events (strong anti-bias cuts) ⇒ Detector independent measurements.





Longitudinal Profiles

Xmax

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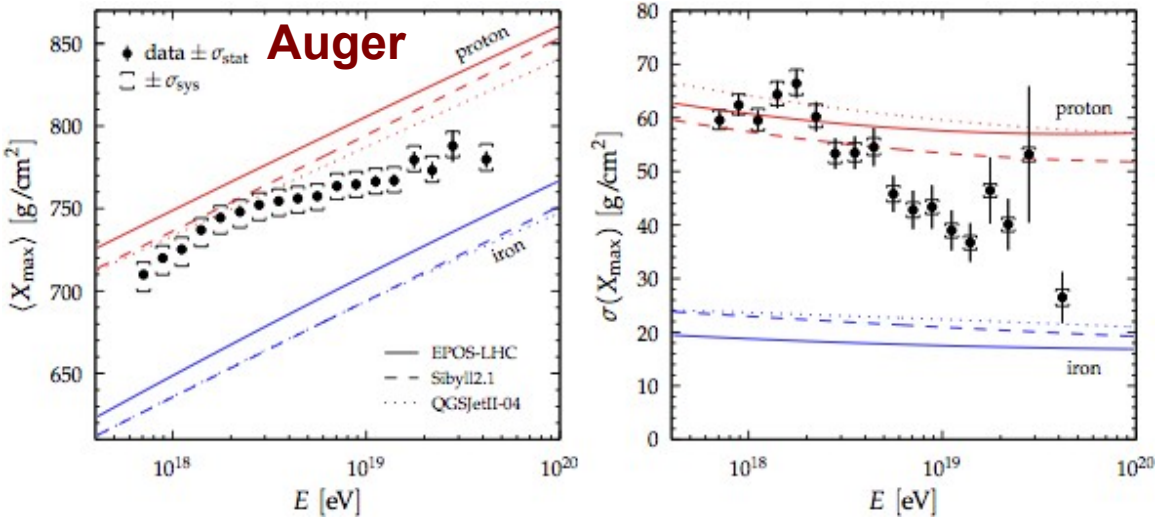
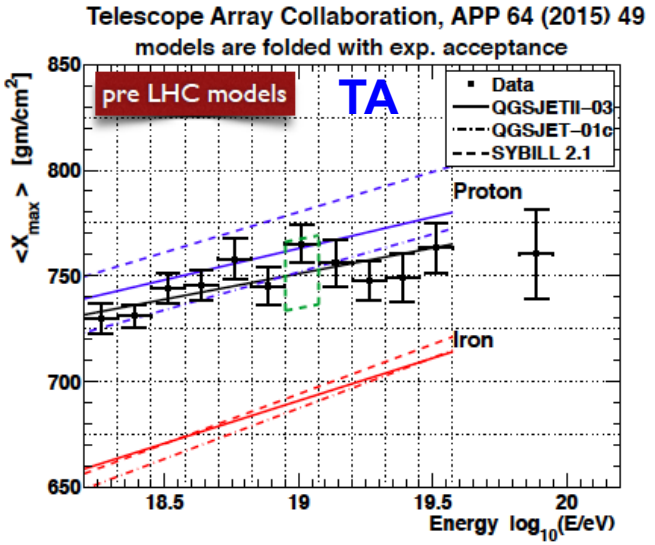


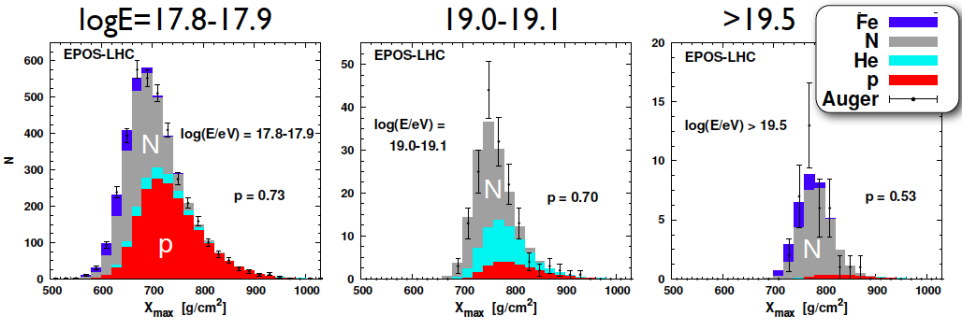
TA distribution is ***not*** detector independent; Instrumental effects folded into MC.



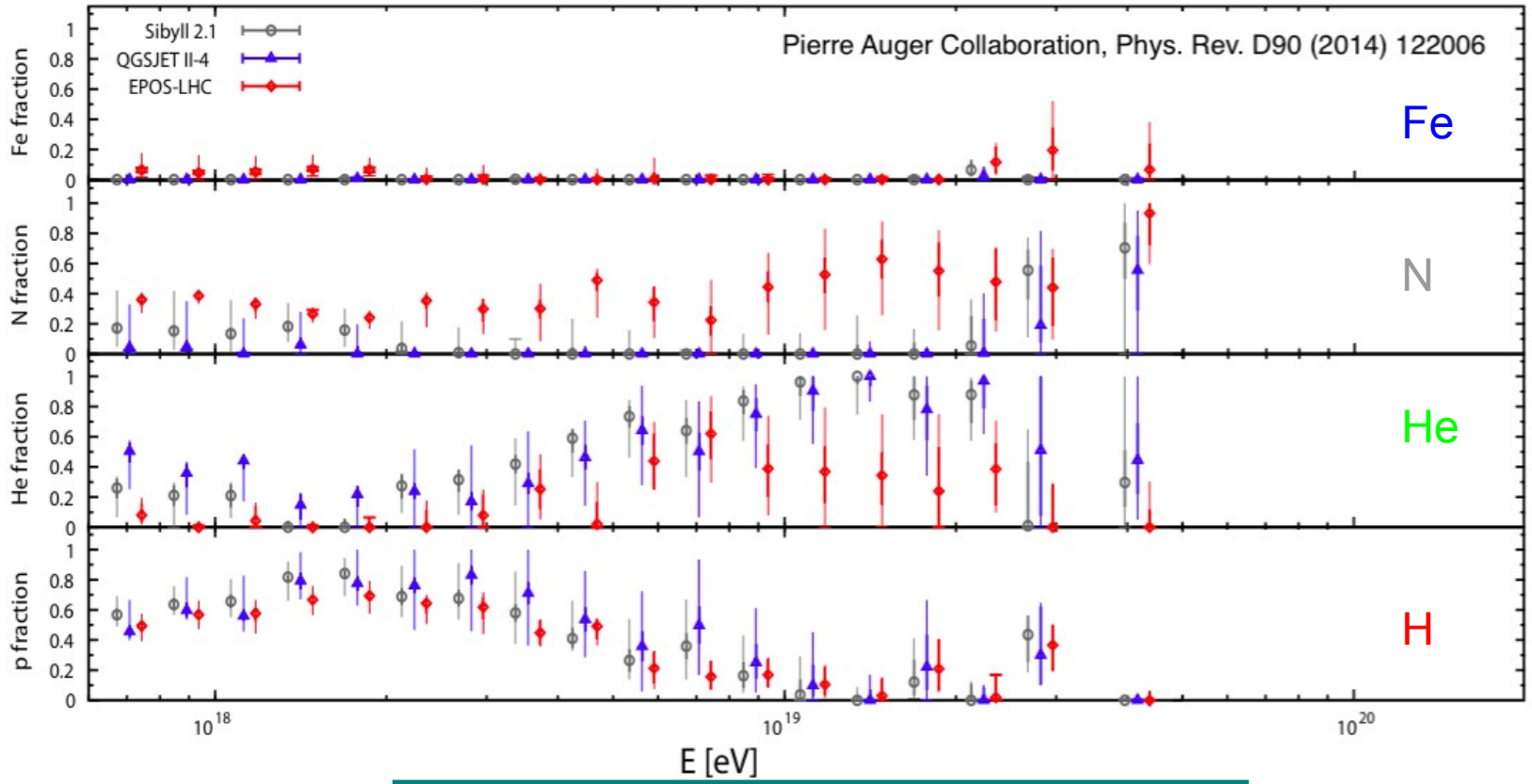
Longitudinal Profiles

Xmax

Here shown for EPOS-LHC



Fitting distributions *PRD 90, 122006 (2014)*

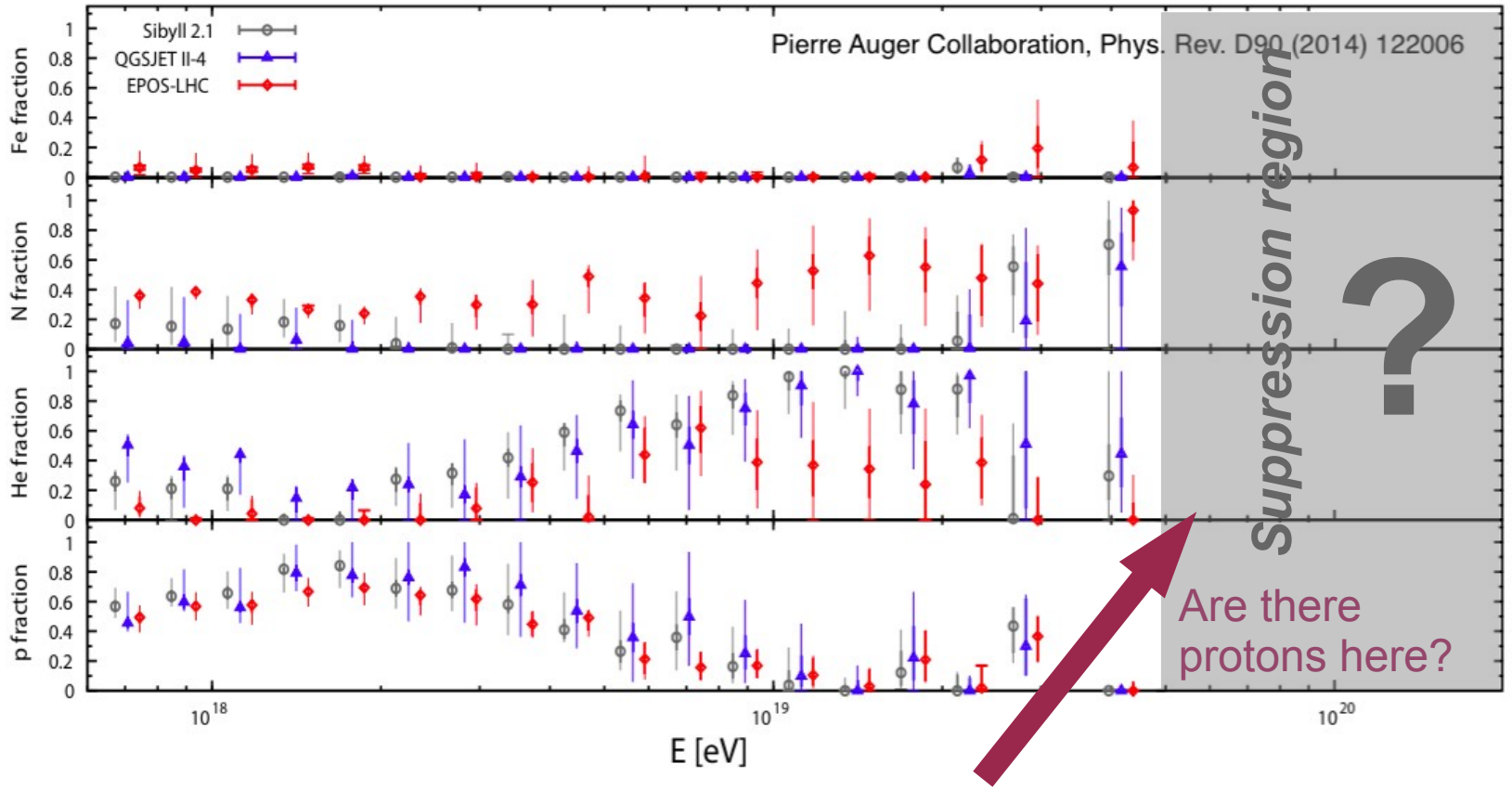


Light component diminish
Heavier take over with energy
→ exhaustion of sources ?

Longitudinal Profiles

Xmax

Fitting distributions *PRD 90, 122006 (2014)*



AugerPrime upgrade

Combining Xmax and spectrum

Astrophysical interpretation in terms of simple scenario

- Homogeneous distribution of identical sources of p, He, N and Fe nuclei
- CR injection = power-law + rigidity cutoff

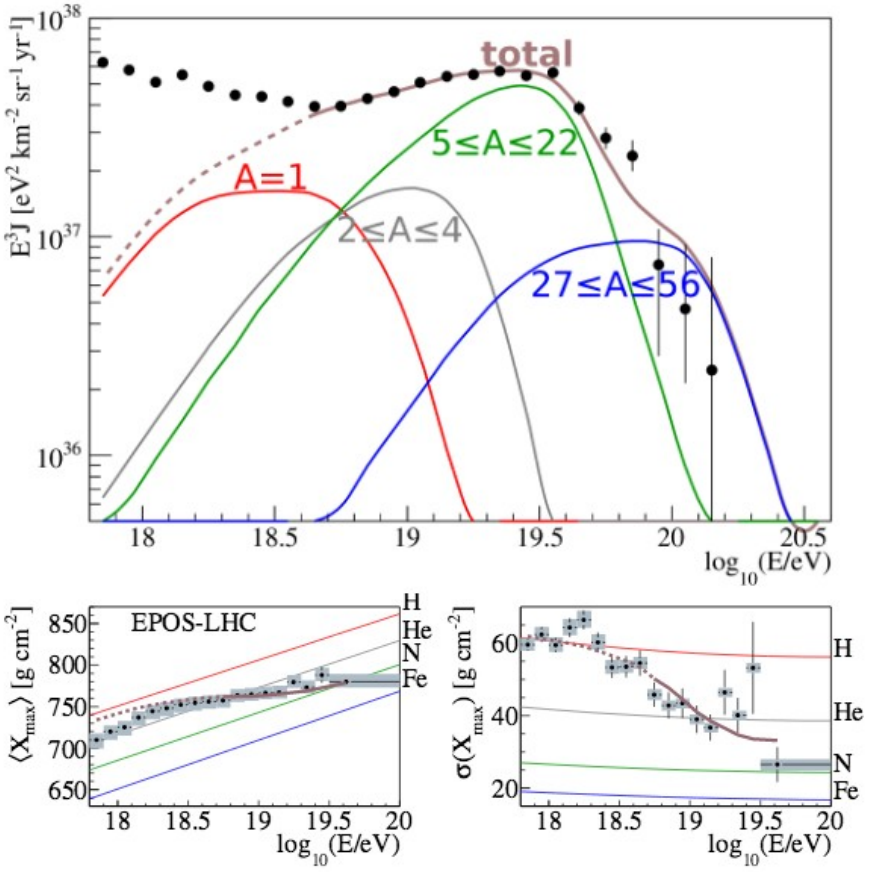
Same basic scenario used in many interpretation papers, e.g.
Aharonian, Ahlers, Allard, Aloisio, Berezinsky, Blasi, Hooper, Olinto, Parizot, Taylor, …
Hard/very-hard injection unless nearby sources assumed

Auger combined fit *(ICRC 2015):*

- 125 data points, 6 fit parameters: injection flux norm, spec. index γ, rigidity cutoff Rcut, p/He/N/Fe fractions;p/He/N/Fe fraction.

Best fit found for very hard injection spectra ($\gamma \leq 1$)
Note: *in this region spectral parameters (γ , Rcut) depend on EBL flux and photo-disintegration cross-sections: R. A. Batista et al., arXiv:1508.0182.*

A. di Matteo et al., Proc. of 34th ICRC, The Hague (2015)



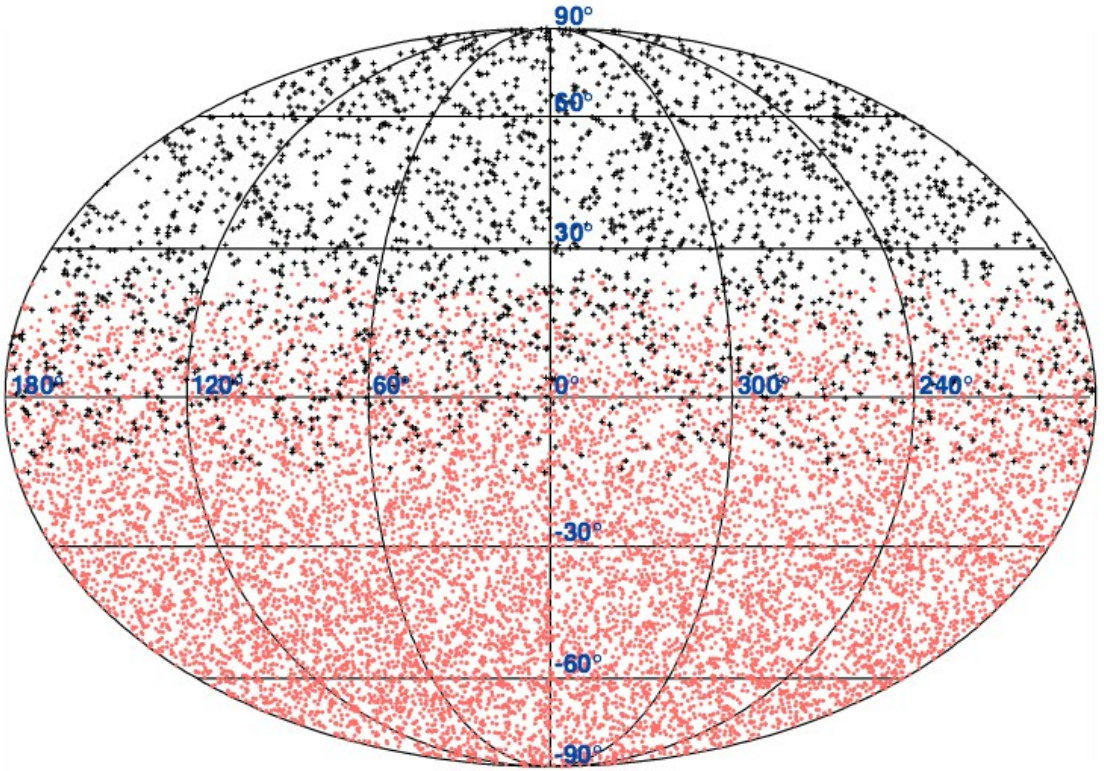
model SPG	best fit	2nd local min
J_0 [eV^{-1} Mpc^{-3} yr^{-1}]	7.17×10^{18}	4.53×10^{19}
γ	$0.94^{+0.09}_{-0.10}$	2.03
$\log_{10}(R_{\rm cut}/{\rm V})$	18.67 ± 0.03	19.84
$p_{\rm H}$	$0.0^{+29.9}$%	0.0%
$p_{\rm He}$	$62.0^{+3.5}_{-22.2}$%	0.0%
$p_{\rm N}$	$37.2^{+4.2}_{-12.6}$%	94.2%
$p_{\rm Fe}$	$0.8^{+0.2}_{-0.3}$%	5.8%
D/n	178.5/119	235.0/119
D (J), D ($X_{\rm max}$)	18.8, 159.8	14.5, 220.5
p	2.6%	5×10^{-4}

SPG = *SimProp code + PSB cross-sections + Gilmore EBL*

Qualitatively similar results for all models, but model-dependent best-fit parameter values

UHECR
Arrival directions

UHECR Sky surprisingly isotropic



Auger and TA Collaborations, ApJ, 794, 172 (2014)

Arrival directions of **Auger** and **TA** events above 10^{19} eV in equatorial coordinates

Large/Intermediate Scale Anisotropy

4-8 EeV Isotropic distribution, Auger: *ApJ 802:111 (2015)*

> 8-10 EeV Dipole-like anisotropy:

Auger: (7.3 $\pm$1.5)%, p=6.4 10^{-5} *Al Samarai, ICRC 2015*
Auger and TA (6.5 $\pm$1.9)% (p=5 10^{-3}) *Deligny, ICRC 2015*

Observed change of phase in RA-analysis
⇨ 10 EeV sources are unlikely of Galactic origin

> 57 EeV hot/warm spots
TA: Ursa Major (5/3.4 σ pre/post trial), *ApJ 790:L21 (2014)*
Auger: CenA (3 σ), *APP 34(2010) 314*

Point source searches

no significant excess found
Auger Collaboration *ApJ 804:15 (2015)*

Summary and outlook

- Flux suppression above ~40 EeV; GZK effect? source exhaustion?
- Xmax (and its RMS) evolution with energy suggest mass becomes heavier at the highest energies;
- Interpreting data in terms of homogeneous sources: *very hard injection ($\gamma \leq 1$) with low cutoff (Rcut < $10^{18.7}$ V) favoured*
- Only small deviations from overall isotropic sky
  either large deflections by B-fields, e.g. due to heavy primaries
  or number of sources is very large (and luminosity low)
- Improved knowledge of mass composition is needed:
  composition in the suppression region, composition enhanced anisotropies, p-astronomy(?),... ⇒ **AugerPrime**